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SCANNING AN OBJECT

The present invention relates to a method and apparatus for scanning an object using a surface measurement
5   probe mounted on a coordinate positioning apparatus. Coordinate positioning apparatus includes, for example, coordinate measuring machines (CMM), machine tools, manual coordinate measuring arms, scanning machines and inspection robots.
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The method and apparatus of the present invention is suitable for scanning teeth and dental parts.

It is known to measure an object by using a surface
15   measurement probe mounted on a coordinate positioning apparatus, for example coordinate measuring machines. The measurement data of the surface of the object thus determined provides a 3D map of the surface of the object.
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A first known method of scanning the surface of an object comprises moving the surface measurement probe along a single direction, for example the x axis, and following the surface of the object along that axis
25   with the probe. This scan provides measurement data along a single plane. To obtain measurement data in the adjacent plane the surface measurement probe must be stopped and reversed to repeat the scan in the next plane and in successive planes, giving a raster scan
30   over the whole surface. This method has the disadvantage that it is slow due to the requirement to stop and reverse the surface measurement probe at the end of each plane.

Another method for scanning the surface of an object
comprises moving the surface measurement probe around
the surface of the object in the xy plane and repeating
the step for adjacent slices of the object translated
5   in the z direction. This method is also slow. It has
the further disadvantage that as the probe force is in
the xy plane, then if the top surface is horizontal it
cannot be measured using the same scan profile, as the
probe will slip on the horizontal surface. To overcome
10   this, a separate scan profile is required for the top
surface

Our earlier International Patent Application No.
WO03/046412 discloses a method of scanning a sample in
15   which the sample is positioned on a mount which is
provided with a generally helical screw-thread so that
the mount and the sample rotate in a helical path. A
probe is positioned at a suitable point on the surface
of the sample so that on rotation of the mount, a
20   spiral scan is produced of the sample.

This method is limited due to its mechanical nature as
it requires a particular mechanical set-up and, for
example, the thread pitch cannot be adjusted.
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The present invention provides a method for scanning an
object with a surface measurement probe mounted on a
coordinate positioning machine, the probe having a
definable servo direction vector, the method comprising
30   the steps of:
        using translational movement of the coordinate
positioning machine to move the probe along an at least
part nominally spiral path about an axis which
intersects the object;

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wherein the servo direction vector for the probe
is directed nominally towards the axis of the at least
part nominally spiral path;

and wherein the servo direction vector for the
5   probe is at an angle to said axis of the nominally
spiral path and at an angle to a plane perpendicular to
said axis of the at least part nominally spiral path.

As the servo direction vector of the probe is at an
10   angle to both the axis of the nominally spiral path and
the plane perpendicular to said axis, this enables
scanning of surfaces both parallel and perpendicular to
said axis, without the probe slipping off the surface
of the object. This is particularly important for
15   objects such as teeth in which information is required
from both the tip and side surfaces. The servo
direction vector is directed nominally towards the axis
of the nominally spiral path to prevent probe slippage.

20   The object may have an unknown surface profile. The
object may have a free form surface.

This method has the advantage that the spiral profile
provides a continuous and fast scan.
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Furthermore, this method may be carried out on any
coordinate positioning apparatus as no mechanical parts
are required to form the spiral scan profile.

30   As the spiral scan profile is not defined by mechanical
parts, the profile dimensions can easily be adjusted,
such as pitch of spiral and angle of the second axis.

The surface measurement probe may comprise a contact

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probe having a deflectable stylus. In this case the
method may comprise a further step of moving the probe
parallel to the direction of the probe servo direction
vector of the probe to control probe deflection.

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The surface measurement probe may comprise a non
contact probe. The method may comprise the further
step of moving the probe parallel to the direction of
the probe servo direction vector of the probe to
10   control probe offset. As the non contact probe moves
along the at least part nominal spiral path, it may be
rotated to keep its line of sight directed towards the
axis which intersects the object.

15   The method may comprise the step of maintaining the
probe on the nominally spiral path by movement of the
probe perpendicular to the direction of the servo
direction vector of the probe.

20   In one embodiment, translational movement of the
coordinate positioning machine to move the probe along
an at least part nominally spiral path about an axis
which intersects the object is achieved by: defining a
second axis along which the probe servo direction
25   vector is parallel, said second axis being at an angle
to said axis which intersects the object; rotating the
second axis for an at least part revolution about the
first axis and translating the second axis in a
direction parallel to the first axis; moving the
30   surface measurement probe to keep it on the axis. The
second axis may intersect the surface of the object to
be measured.

The servo direction vector of the probe may be angled

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at 45 degrees to the axis intersecting the part.

The angle between the probe direction vector and the axis which intersects the object may be varied during the scan.

The surface measurement probe may comprise a non-contact probe, for example an optical, capacitance or inductance probe.

A second aspect of the present invention provides a method for scanning an object with a surface measurement probe comprising the steps of:

     defining a first axis of the object;

     defining a second axis, said second axis being at an angle to the first axis;

     rotating the second axis for an at least part revolution about the first axis and translating the second axis in a direction parallel to the first axis;

     moving the surface measurement probe to keep it on the second axis.

The probe may be servoed in the direction of the second axis to keep the probe at the desired distance from the object. The probe may be servoed in a direction perpendicular to the second axis to keep the probe on the second axis.

Preferably the second axis intersects the surface of the object to be measured.

A third aspect of the present invention provides an apparatus for scanning an object comprising:

     a surface measurement probe mounted on a

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coordinate positioning machine, said coordinate
positioning machine having drive means to enable the
probe to be driven translationally in several axes;
    a controller which controls said drive means to
5   move the probe along an at least part nominally spiral
path about an axis which intersects said object;
    wherein the controller controls the drive means
such that the servo direction vector of the probe is
directed nominally towards the centre of said axis of
10 the at least part nominally spiral path;
    and wherein the controller controls the drive
means such that the servo direction vector of the probe
is at an angle to said axis of the at least part
nominally spiral path and at an angle to a plane
15 perpendicular to said of the at least part nominally
spiral path.

Preferred embodiments of the invention will now be
described by way of example with reference to the
20 accompanying drawings, wherein:
    Fig 1 is a perspective view of the object to be
scanned;
    Fig 2 illustrates the spiral scan profile;
    Fig 3 illustrates the scan profile for a series of
25 half revolutions of the second axis;
    Fig 4 illustrates measurement of a surface having
an undercut; and
    Fig 5 illustrates a plan view of the scan profile.

30 As illustrated in Fig 1 an object 10, to be measured
e.g. a tooth, is mounted 12 on a mount of the
coordinate positioning apparatus. The coordinate
positioning apparatus has drive means (not shown) which
enable translational movement of a probe 24 mounted on

it along the x,y and z axes. Such movement is
controlled by a machine controller 15. An axis of
rotation 14 of the object is specified by the user.
This may for example be the z axis of the part
5   coordinate system of the object. The rotational axis
14 may be defined with respect to the mount 12 by the
object 10 being mechanically aligned to this axis when
mounted on the mount. A second axis 16 is defined
which is at an angle φ to the rotation axis 14 and
10   which intersects the surface of the object 10. The
second axis 16 may be at any angle to the rotation axis
14 (but not parallel) and Fig 1 shows the second axis
being at 45°. The second axis 16 is rotated about the
axis of rotation 14 and is translated parallel to the
15   axis of rotation 14 thus creating a spiral profile.
Fig 2 illustrates the spiral profile 18 created by this
movement of the second axis about the axis of rotation.
As described in more detail below, a probe is moved
along the spiral profile created by the movement of the
20   second axis to scan the object along this spiral
profile. Fig 3 illustrates the scan profile 20 created
when the second axis is rotated a part revolution about
the axis of rotation and translated parallel to the
axis of rotation. This scan profile is suitable for
25   use with a probe having a T stylus 22 as illustrated.
A surface measurement probe 24 is mounted on the
coordinate positioning apparatus for relative movement
with respect to the mount 12. The probe 24 has a
deflectable stylus 26 with a surface contacting tip 28.
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The probe 24 follows the spiral profile created by
movement of the second axis 16 and thus scans the
object 10 by following a spiral profile.

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The servo direction vector of the probe is directed
along this second axis. This is the direction in which
the probe is servoed by the coordinate positioning
apparatus to control the stylus deflection of the probe
5   (or for a non-contact probe, to control the offset of
the probe.)

Movement of the probe is controlled by an algorithm
having two components. The first component keeps the
10 probe on the second axis. This is accomplished by
determining the position of the stylus tip of the
probe, determining the nearest position on the second
axis to the stylus tip and moving the probe in a
direction perpendicular to the second axis back onto
15 the second axis.

The second component of the algorithm controls the
probe deflection. In this case the probe is moved
parallel to the second axis to provide the desired
20 probe deflection.

Both of the algorithm components are calculated as
position demands.

25 In the present example, the second axis has an angle of
45°. This is convenient for most applications because
it will intersect with both the side and top surfaces,
it enables both of these surfaces to be scanned in a
single scan. This is particularly important where
30 measurement of the top surface is important, for
example for teeth. For measurements of surfaces both
parallel and perpendicular to the rotational axis 14,
the second axis must be at an angle to the rotational
axis and to the plane perpendicular to that axis.

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An advantage of this method is that the angle of the
second axis may be varied. Fig 4 illustrates an object
30 having an undercut 32. In the embodiment above the
5   second axis was angled at 45° to the axis of rotation
(shown by dashed line 34). This allows measurement of
an undercut at an angle of 45° or below. An undercut
having an angle of greater than 45° is not intersected
by the second axis angled at 45° and thus cannot be
10   scanned using this profile. However if the angle of
the second axis is changed, for example to 90° to the
axis of rotation, this new second axis 36 now
intersects the undercut which can be scanned using the
spiral profile. The angle of the second axis can be
15   changed during the scan. Thus objects with sharp
undercuts can still be scanned in a single scan profile
which has the advantage of enabling a fast scan. This
is particularly relevant for scanning objects such as
teeth which have undercuts.
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The angle of the second axis may be changed
automatically using stylus deflection data to determine
when to change the angle. For example, referring to fig
4, the object 30 may be scanned upwards from at or near
25   the bottom of the object using a horizontal second axis
36. When the stylus tip reaches the corner 38 of the
undercut 32, the stylus will be deflected in -Z and the
angle of the second axis will in response change
automatically to 45°. Alternatively, the angle of the
30   second axis may be changed at a predetermined position
in Z.

The algorithms used to control the position of the
probe will now be described with reference to Fig 5.

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In a first step the rotation angle demand for the next frame is calculated. (This can exceed 2Π.)

5 $\theta = \Omega T$

where θ is the rotation angle of the second axis Ω is the rotational velocity of the second axis and T equals time.

10 In a next step, the rotation matrix is created:

$$\text{Rotation} := \begin{pmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Where "Rotation" is the rotation matrix.

15 In a next step the sensor axis direction is calculated:

$$\text{Direction} := \text{Rotation} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ 0 \\ \frac{1}{\sqrt{2}} \end{bmatrix}$$

Where "Direction" is the sensor axis direction.

20 The origin translation in z due to the thread pitch is then calculated.

$$\text{Origin} := \begin{bmatrix} 0 \\ 0 \\ \frac{\theta}{2.\pi} \cdot \text{Pitch} \end{bmatrix}$$

25 Where "Origin" is the origin translation in z and "Pitch" is the thread pitch.

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Next the scan position demand is calculated. This is
the nearest point on the second axis to the current
machine position, where "machine" is the position of
5   the centre of the stylus ball when there is no
deflection.

ScanPositionDemand:= [(Machine - Origin).Direction].
Direction + Origin

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The probe deflection error is calculated from:

Deflection error:= |Probe deflection| - Nominal
deflection

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Where "Probe deflection" is the actual probe deflection
and "Nominal deflection" is the desired probe
deflection.

20   The probe deflection error is used to calculate the
deflection control vector:

ProbePositionDemand:= DefError.Direction

25   Where "DefError" is the probe deflection error and
"direction" is the direction parallel to the second
axis along which the probe is moved.

The position demand vector can thus be determined from
30   the deflection control vector and the scan position
demand vector:

PositionDemand:= ScanPositionDemand +
ProbePositionDemand

The velocity demand can thus be created:

$$VelocityDemand := \frac{PositionDemand - \text{Machine}}{\delta t}$$

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Although the above description describes the use of a
contact probe, the method is also suitable using a non-
contact probe e.g. an optical, capacitance or
inductance probe. If a 1-D non-contact probe is used,
10 the probe will need to be rotated to keep it directed
at the surface of the object as the probe follows the
spiral profile for example it may be directed towards
the rotational axis of the spiral path. However using
this method, the direction in which the probe must face
15 is known. Offset of the non-contact probe may be
adjusted by moving the probe parallel to the second
axis in a similar manner to how probe deflection is
adjusted for a contact probe.